WOOD2WOOD

A Wood-to-Wood Cascade Upcycling Valorisation Approach

» Deliverable 5.4

Better Separation and Quality Control Systems (version 1)

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Dissemination Level		
PU	Public	X
RE	Restricted to a group specified by the consortium	
CO	Confidential, only for members of the consortium (including the European Commission Services)	

Legal Disclaimer

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GLOSSARY OF ACRONYMS

Acronym	Extended Definition
AR	Augmented Reality
CAD	Computer-Aided Design
Cobot	Collaborative Robot
CDW	Construction and Demolition Waste
D3.1	The first deliverable of the third work package
HMD	Head-Mounted Display
HRC	Human Robot Collaboration
KER	Key Exploitable Result
KPI	Key Performance Indicator
ISO	International Organisation for Standardisation
LED	Light-Emitting Diode
MR	Mixed Reality
MQTT	Message Queuing Telemetry Transport
UR	Universal Robots
UDP	User Datagram Protocol
ROS	Robot Operating System
RRT	Rapidly-exploring Random Tree
STOMP	Stochastic Trajectory Optimisation for Motion Planning
W2W	Wood-to-Wood
WP	Work Package
XR	eXtended Reality

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EXECUTIVE SUMMARY

The ‘advanced separation and sorting technologies’ component of the Wood-2-Wood project includes a collaborative picking line comprising a conveyor along which human workers collaborate with robotic systems in order to ensure the sorting quality. At the collaborative human-robot disassembly station a cobot assists the human operator in removing foreign objects from wood pieces so as to ensure that the sorted wood quantities are free from impurities. The cobot’s role is to handle physically demanding or repetitive subtasks, such as moving and stabilising the workpiece or exposing fastening elements, while the human worker remains in control of critical decisions and fine manipulation actions guided by extended reality devices and user interfaces. In this first period of the project the design and prototyping phase was completed. A safety-by-design approach is being pursued by considering proper configuration of the cobot and ensuring that the worker is always aware of the cobot’s intent which is visualised on their mixed reality head-mounted display. As a conclusion of the final phase of the implementation, the functional aspect of spending an entire work shift wearing a head-mounted display is also considered by putting it to the test, in terms of safety awareness and comfort, against alternative mixed reality modalities such as a video wall and projection-based AR.

1. INTRODUCTION

1.1. PROJECT INTRO

The W2W project develops a comprehensive framework for multi-dimensional cascade valorisation of wood waste from construction, demolition and furniture manufacturing, consisting of four core components: i) advanced separation and sorting technologies; ii) upcycling processes and technologies to recover wood or resources from waste; iii) digital tools to improve circular flows of secondary materials; iv) a supportive framework in policy, market, and skills.

W2W will demonstrate efficient and sustainable value chains in three use cases for the production of wood without pollutants, biocomposite building materials, biopolymers, polyols, chemical detergents, and the recovery of nutrients using technologies and tools that allow the selection of optimal cascade valorisation paths. The project's holistic approach aims to reduce the demand for virgin materials, reduce the amount of waste that ends up in landfills or incineration facilities, allow for the creation of new value-added products from waste materials, and support the transition towards a circular economy by promoting closed-loop systems where materials are continually repurposed and reused, thus extending their useful life.

1.2. PURPOSE OF THE DELIVERABLE

The purpose of this deliverable is to document the progress of the development of the digital tools that allow human-robot collaboration along the wood sorting line. This first version of the collaborative sorting line for the separation of metallic objects from wood pieces builds on deliverable D5.3 as it is a part of a longer wood separation system. It also serves as the foundation and stepping stone for the development of the final version within the next 18 months of the project.

The related key exploitable results and performance indicators associated with this deliverable and the related tasks are further detailed in the corresponding deliverables and listed below:

- **KER 3:** Optimised separation enabled by Human-Robot Collaboration and MR technologies
- **KPI O2.1:** To achieve a 95% accuracy of wood separation from mixed CDW sources.
- **KPI O2.3:** To allow collaboration between Robots and humans with non-latency constraints

1.3. INTENDED AUDIENCE

The primary audience of this report is the wider public and any third parties, researchers and practitioners who are interested in upgrading their fully automated or fully manual conveyor picking lines to collaborative. It is also addressed to the European Health and Digital Executive Agency services so as to assess the status of the W2W-task T5.5 and T5.6 in the context of the project's continuous reporting obligations. It also serves as the documentation of the state and intent for the development to the consortium party members so that they can coordinate their effort accordingly, where necessary.

1.4. STRUCTURE OF THE DELIVERABLE

The next section of this report provides the objectives of the sorting line, while Section 3 is an overview of the collaborative sorting line, its concept and scope in the context of tasks T5.5 and

T5.6. Section 4 describes the process of designing and developing the first version of the constituent parts of the collaborative sorting line prototype and section 4 provides further details on the components. Section 5 brings together the human and the robotic aspect in terms of interactions and safety.

2. OBJECTIVES OF THE COLLABORATIVE SORTING LINE

2.1. Context and Motivation

Valorisation of wood available in Construction and Demolition Waste (CDW) and furniture waste remains challenging because of the numerous contaminants and foreign materials that require removal before the material is processed again. Typical examples of such materials are assembly and fastening elements, such as bolts, nails, and screws. These are commonly separated using numerous mechanical processes in series such as shredding, magnetic separation and eddy current separation. However, this design makes separation of wood waste based on its type more difficult as it imposes homogenizing the entire waste stream. Disassembling the elements from the initial workpieces would simplify wood sorting based on its type.

State-of-the-art approaches in robotic disassembly systems have shown potential in structured environments, typically focusing on products with standardized designs and predictable fastening methods ("Introduction to Remanufacturing," 2022). However, in many real-world scenarios, e.g., reclaimed wood from furniture or construction applications, the geometry, location, and condition of assembly elements are highly variable. Current robotic systems struggle to generalize across these variations, particularly in tasks that require fine perception, adaptive manipulation, or decision-making (Foo et al., 2022).

Given these constraints, a purely automated disassembly solution remains currently infeasible for such tasks. Fully autonomous systems lack the cognitive capabilities, perceptual accuracy, and dexterous control that human workers naturally have. On the other hand, relying solely on manual labour includes ergonomic risks, reduces scalability, and limits process efficiency. Furthermore, disassembly operations due to their monotonous, labour-intensive and mentally unchallenging nature are unattractive for human workers. Some tasks also involve inherent safety risks due to the use of sharp tools or the exposure to hazardous materials.

2.2. System Overview

To address these challenges, W2W has proposed a collaborative human-robot disassembly station, where a cobot assists the human operator in removing assembly elements from wooden structures. In this setup, the robot handles physically demanding or repetitive subtasks, such as moving and stabilizing the workpiece or exposing fastening elements, while the human worker remains in control of critical decisions and fine manipulation actions. The human is further assisted by extended reality interfaces, providing intuitive guidance, system status updates, and spatially aligned visualizations to support situational awareness and task coordination.

This collaborative arrangement offers several advantages. It leverages human expertise and adaptability while offloading physical effort to the robot, improving both safety and ergonomics. Furthermore, it increases process efficiency by enabling parallel action and enhances traceability and consistency through system-assisted guidance and monitoring. The primary objective of the system is to enable safe, efficient, and semi-automated removal of diverse fastening elements, supporting a wider goal of sustainable material recovery. Secondary objectives include improving operator working conditions, demonstrating the applicability of MR technologies in human-robot cooperation, and creating a flexible architecture adaptable to multiple disassembly use cases.

2.3. Safety Considerations For Human-Robot Collaboration

Safety is a feature that needs to be ensured in every human-robot interaction system. Human-Robot Collaboration systems include the maximum level of human-cobot interaction, as both robot and human worker share workspace and work together simultaneously on the same task. In such settings, adhering to safety standards and taking measures based on them is essential to prevent accidents, reduce operation risk, and increase user trust.

The most popular safety standards for robot applications are ("ISO 10218-1: Robots and robotic devices — Safety requirements for industrial robots, Part 1: Robots," 2011) and ("ISO 10218-2: Robots and robotic devices — Safety requirements for industrial robots, Part 2: Robot systems and integration," 2011). These standards set the safety requirements for industrial robots and robot systems in general, while they make a short mention on human-robot collaboration. However, the ("ISO/TS 15066:2016 Robots and robotic devices — Collaborative robots," 2016) technical specification acts as a supplement providing special guidelines for collaborative robot applications. These standards determine allowed types of interaction between robot and human, enumerate contact force limits, and define collaborative operations such as speed and separation monitoring, power and force limitation, and hand guiding.

The use of a cobot, rather than an industrial robot, does not guarantee by itself a safe collaborative application. The safety design features of the robot, such as torque sensors or reduced power, must be properly configured for the general application environment. In addition, several issues not related to the cobot design influence the safety of the application. These include:

1. Workpiece: Processing of the workpiece may create hazardous byproducts
2. Task application: The nature of the task itself may expose the operator to risks
3. End-effector and tools: Tools mounted on the robot may introduce additional hazards, particularly if sharp, heavy, or powered.
4. Robot payload: Higher payloads increase the potential for injury in case of unintended contact.
5. Operator’s skills: Operator’s training and familiarity with the system affect both safety and task efficiency.

As an example of unsafe collaborative application, consider the scenario where a collaborative robot handles a powered screwdriver or a claw hammer. Despite the collaborative design and features of the robot, the use of an electrically powered or a heavy sharp tool introduces risks that are difficult to mitigate, if not impossible.

In collaborative applications, design process should be guided by the safety requirements. This ensures that all interaction scenarios remain within acceptable safety limits. In the example use case mentioned above, the use of a hazardous end-effector could rendered the application unsafe without increased safety measures. Thus, the gripper must be inherently safe, especially when humans are present within the robot's workspace. This includes avoiding sharp edges, limiting gripping force when appropriate, and considering failsafe mechanisms in case of unexpected contact e.g. clumping. Furthermore, using the XR as the means to facilitate human-robot collaboration allows the introduction of additional safety-related mechanisms. Such features will include visual cues to always be aware of system status, XR UI controls to allow the user to halt operation and graphical representation of the cobot's next moves so that the worker is aware of its intent and can anticipate its movements.

Finally, a critical requirement for any collaborative application is the execution of a comprehensive risk assessment. This assessment must evaluate all potential hazards arising from the robot's movements, tooling, workpiece and environment interactions. It informs the selection and configuration of safety measures, ensuring that the system can safely operate in the presence of human workers. Although the importance of risk assessment is acknowledged in this project, no formal risk assessment will be performed as part of this work (see version 1). This document focuses on the conceptual and technical design aspects of the collaborative station, as well as the initial steps of integration. A comprehensive risk assessment should be performed prior to full deployment and operation, always considering the aforementioned safety standards.

3. PROTOTYPE DESCRIPTION

3.1. Overview of the Collaborative Sorting Line

The premise of our work for better separation and control systems is similar to what is discussed in (Chen et al., 2023) and extends what is presented in (Aberger et al., 2025). (Chen et al., 2023) used an augmented reality headset as a communication interface for collaborative construction waste sorting; their aim was to strike a balance between sorting efficiency (measured by quickness and accuracy) which is considered a challenge in the fully automated case and occupational health and safety as humans are more efficient in sorting tasks but they are often exposed to hazardous materials. The human's role is primarily to observe and intervene to correct the cobots' sorting errors. In (Aberger et al., 2025), the manual sorting process is augmented with projection-based augmented reality to highlight objects that should be handled by human workers. In both cases, a camera observes the scene and directs further actions.

3.1.1. Scope

The user under consideration is a worker at a facility where wood waste is shredded, separated from foreign objects and sorted for further processing according to the characteristics of wood material. The user story is formalised with the following statement: *as a worker at a wood-waste sorting facility I need an interface so that I can collaborate with a cobot to remove foreign items from wood pieces that move along a conveyor line*. As described in deliverable D5.3, only one segment of the entire W2W sorting line is collaborative. Wood pieces with metallic objects embedded in them are directed to this line so that humans in collaboration with cobots remove any foreign objects and extract the clean wood material.

3.1.2. Concept

An illustration of the collaborative sorting line concept is shown in Figure 1. A perception module comprising an array of sensors observes the waste stream on the conveying systems at the start of the collaborative line and directs further actions based on the identified objects. The perception module detects and communicates in real time information related to the type and the location of the objects on the conveyor to the task planning module which is responsible for allocating a task to either the cobot directly or the human worker by visualising information on XR devices. The human worker is also responsible for verifying the communicated instructions or intervening if they are deemed incorrect and feedback the correction to the planner. As the cobot lacks the dexterity to remove metallic objects embedded to wood pieces, this task is allocated to the human worker. The cobot's main role is twofold: remove items from the belt and place them on the workbench, especially if the worker is already busy with another item or pick and hold items while the worker removes foreign objects from them. One of the most challenging aspects is ensuring that the communicated instruction was indeed carried out by either the cobot or the human so that the planned log of the processed items reflects the actual work that has been done. To this end, either a sensor integrated to the HMD will be used or an external one monitoring the conveyor line or the workbench. Several setups of the common collaborative workspace will be investigated, as illustrated in Figure 2, which will include one cobot, one workbench with the necessary tools (e.g. screwdriver and pliers), one or more workers, and several sorting bins.

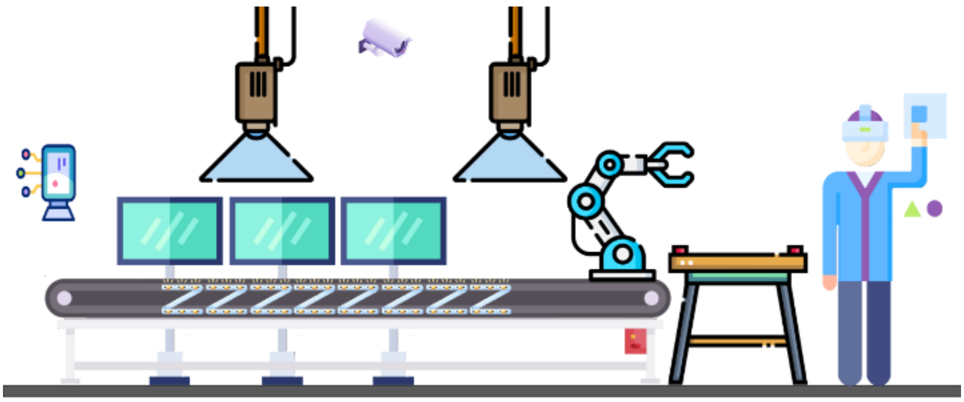

Figure 1. (Left) Illustration of the collaborative sorting line concept (icons from Freepik, 2025)

3.2. Robot-Centric Part

The collaborative robot has two main functions: i) handle fully automated subtasks, and ii) assist the human operator for operations that it cannot carry out independently. An e subtask of the first category is a pick-and-place operation from the conveyor or a similar buffer for later processing. On the other hand, the cobot can hold a workpiece in an appropriate position and orientation to facilitate the removal process from the human worker. The collaborative robot needs to always ensure the safety of the worker and its environment through intelligent planning and real-time processing of perception data.

A commercially available collaborative robot is chosen based on the payload and the workspace dimensions. It is controlled in real-time with high precision and short response time, while planning with collision avoidance is always performed. Coordination between the cobot and the human worker is managed by a decision-making module that tracks the state of operations and subtasks performed within the workcell. It performs high-level control of the collaborative robot, directing it to proceed to its next operation based also on its previous actions and the interaction with the human worker. A perception module is employed to perform numerous computer vision tasks. Using 3D sensing data with sufficient accuracy, the workpieces are localized within the robot workcell, and their positions are communicated to the cobot for manipulation. Furthermore, the perception module detects fastening and assembly elements in the workpiece employing ML-based techniques to come up with the optimal manipulation strategy. Finally, a finger gripper is designed to accommodate safe and efficient manipulation of the parts.

3.3. Human-Centric Part

From a human's perspective there exist several ways to facilitate the collaboration between a human worker and a robotic system, with the main goal being having a common awareness and understanding of each other's intent and task assignments. In this context, the term 'robotic system' refers to all the parts comprising the automated wood-sorting line and not strictly a cobot. The means to achieve this, in the scope of this work, involves light structured in such a way to communicate information to the human who is collaborating with a robot to achieve the common task of removing metallic objects from pieces of wood. The four XR modalities which are being developed include one primary which is based on a head-mounted mixed-reality display and three secondary hardware configurations which can be used in tandem or separately: a video wall along the conveyor, a backlit conveyor combined with a translucent belt and a projection-based augmented reality setup (see Figure 1). For the last few years, investigating the use of MR HMD in several occupations has gained a lot of traction not only as a training tool but also as an on-the-job aid. However, using a headset for long periods of time is a challenge in terms of acceptance by the user and also from a practical perspective when it comes to power efficiency, whether that is battery life of cable management. For this reason, the efficiency and effectiveness of the MR HMD-based collaborative sorting workflow will be compared against more traditional approaches in order to assess the advantages and disadvantages of each one.

4. DEVELOPMENT

This first version of the collaborative sorting tools did not include direct testing between a human and the cobot and was based on simulation environments to ensure that all features are fully developed and mature enough to be deployed in an operational environment for validation before demonstration. Thorough testing and trials will be undertaken within an iterative optimisation phase during the next period of the project.

4.1. Robotic Hardware and Software

4.1.1. Collaborative robot

The collaborative robot selected for the application had to fulfill numerous requirements related to its i) workspace dimensions, ii) payload limits, iii) ease of integration and programming, as well as iv) safety compliance. These criteria have led to the selection of a UR5e collaborative robot by Universal robots.

Starting from the workspace limits, a simple design was made in CAD software placing a standard cobot in a representative environment on a standard table as workbench, with a regular conveyor, a custom finger gripper (see Subsection 4.1.3) a human worker and 2 bins. The 3D design is shown in Figure 3 and as mentioned in the previous section, the placement of the station components is not finalized, and several setups will be evaluated in later stages of the development (see Figure 2). This process allowed us to evaluate the minimum reach, and consequently the workspace dimensions. A minimum reach of 700 millimeters was found sufficient to perform all tasks with most configurations, given that the common dimension for the conveyor width is 600 millimeters. The UR5e[1] robot has a reach of 850 millimeters.

Since a relatively light gripper was designed (see Subsection 4.1.3), the weight of the wooden workpieces will not be greater than 0.5 kilograms and the forces applied by the human worker to the workpieces are restricted, the maximum payload of 5 kilograms of UR5e was deemed sufficient. However, special care should be given for large offsets of the center of gravity, because the payload may decrease down to 3 kilograms.

The chosen collaborative robot is well-known for its customizability to a variety of applications and tasks. During previous projects with this particular robot model, it was concluded that it is a great choice for having full control of its motion due to the high-quality, UDP-based interface provided by the manufacturer ("Real-Time Data Exchange," n.d.). This interface allows to control in a soft real-time fashion the individual motors of the robot with a frequency of 500Hz without disabling any of the existing safety features. Furthermore, the robot manufacturer has actively supported the robot, while the research community has integrated it through many projects. Thus, there are already many freely available implementations and code sources to begin with, while we proceed with our developments. Finally, *URSim*[2] is an offline simulation tool provided freely by the manufacturer that enables us to perform full simulations and test the entire cell, without purchasing a license or being restricted to a specific OS, conditions that are common for most robot manufacturers.

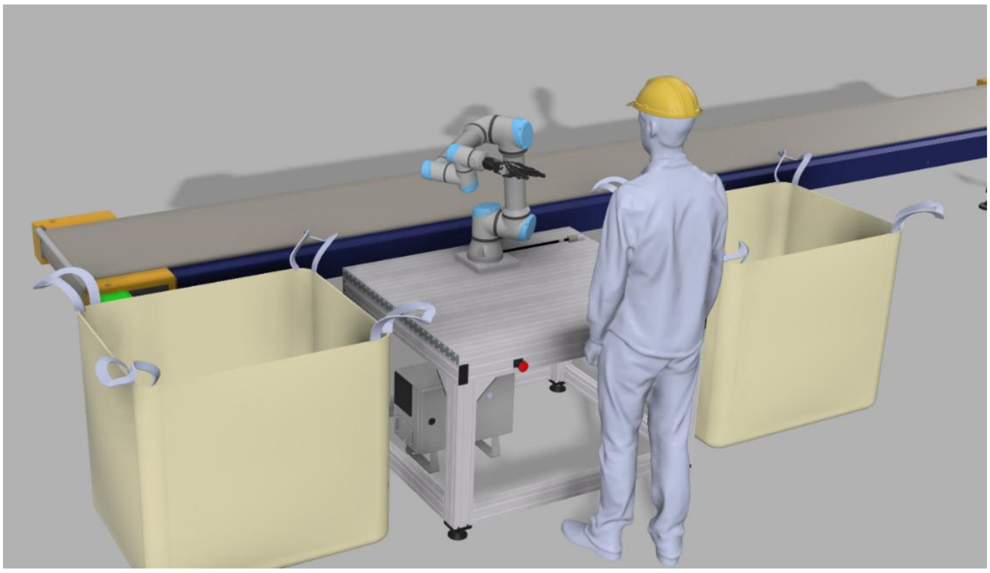

Figure 2: Indicative design of the HRC station with the collaborative robot

Human worker safety is of essence for the application and the selected robot should comply with the human-robot collaboration safety standards (see Subsection 2.2). For this particular robot, the 4 collaborative operation techniques are supported by the robot and numerous safety functions

[1] https://www.universal-robots.com/products/ur5e/

[2] https://www.universal-robots.com/download/software-e-series/simulator-non-linux/offline-simulator-e-series-ur-sim-for-non-linux-5126-lts/

have been implemented by the manufacturer ("Universal Robots e-Series User Manual: UR5e," n.d.). Nevertheless, the integrator is responsible at the end for employing these functions correctly and configuring their settings.

4.1.2. Robot Planning and Control

As hinted previously, planning and real-time control of the UR5e robot relies on the open-source framework *ROS2*. There are *ROS2* distributions available for multiple OS releases, but not all of the distributions are actively supported at this moment. Therefore, the *ROS2 Humble* distribution was selected as the most stable, while it will be supported until 2027. Furthermore, this distribution is natively supported by the *Ubuntu 22.04 LTS* OS release, which is versatile enough to support most of our perception and robot planning needs.

The robot manufacturer provides a great interface for controlling the robot in a reliable way without the use of a real-time operating system. Although a real-time kernel is suggested, it was noted during our initial experiments in simulation with *URSim* and with the real hardware that the effect of a real-time kernel on the performance is negligible. However, the choice of real-time kernel may be evaluated in further experiments if necessary.

Although there are multiple planning frameworks for industrial robots such as *OROCOS*[3] and *OpenRAVE*[4], the most popular for research applications and prototype is *MoveIt2*. It is open source, relying solely on *ROS2*, and it is used for motion planning, control and perception integration with a large range of industrial robotic arms. Libraries that already integrate UR5e cobot into *MoveIt2* is already provided by the robot manufacturer.

Kinematics of robotics arms are employed among others for collision detection, motion planning, transformation between joint and cartesian spaces, visualization and reachability analysis. The kinematics of industrial robotic arms with 6 Degrees-of-Freedom are well studied and easy to solve analytically with existing kinematic solvers when the last 3 joints form a spherical wrist. However, universal robots do not fall into this category and some adjustments are required. For serial manipulators, solving analytically the forward kinematics is trivial and no special attention was required for UR5e. However, we formed an analytic solution for the inverse kinematics, since none was found available.

Moveit2 has been extensively used in research to develop benchmark motion planning algorithms for robotic arms from different categories. As a result, there are numerous motion planners that can be used for this application without the need to develop a new one. Nevertheless, each algorithm has some advantages and disadvantages depending on the requirements of the task and many have been developed for special applications.

During initial development and testing in simulation for this project, some fundamental algorithms were evaluated such as RRT-connect (Kuffner and LaValle, 2000) from the category of sampling-based motion planning algorithms, STOMP (Kalakrishnan et al., 2011) from the category of optimisation-based planning algorithms, as well as a deterministic algorithm approximating the motion planners of standard robot arms. Although more tests will be required during the actual

[3] https://orocos.org/

[4] https://openrave.org/

use-case, it was noted from the experiments with the planners that STOMP performed well, being able to generate a valid, collision-free path plan in most cases.

4.1.3. Robot Simulation

Before deploying the robot in the actual workspace, a simulation of the workcell was created in a robotics simulation environment compatible with *ROS2* and *MoveIt2*. Due to its well-known integration with the aforementioned tools and its open-source nature, *Gazebo Classic* was chosen. This tool simulates a variety of sensors used for perception like RGB camera, 3D cameras and LiDAR sensors, as well as force/torque sensors and inertial measurement units. Its modular and extensible nature allows to create custom plugins to simulate any kind of component into the environment, such as gripper motions, object manipulation and animated human actors.

The design of the workcell that had been previously created in CAD software was exported to an appropriate format in order to be imported to Gazebo. The simulated workcell is depicted in Figure 3. To simplify and accelerate the simulation, objects that do not affect the robot operation e.g. the control box were removed.

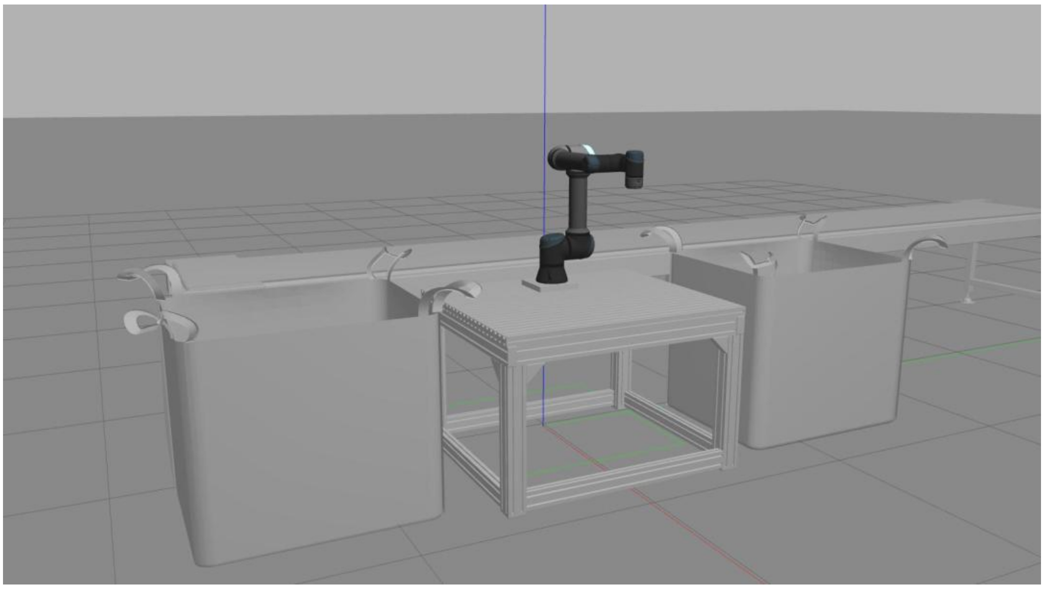

Figure 3: Simulation of the workcell in Gazebo simulation environment

This simulation has enabled some first stages of systematic testing of edge cases, failure scenarios, and latency-sensitive operations without risking hardware damage or compromising operator safety. An iterative design process was followed for the gripper geometry, the workspace layout and the motion planning algorithms in order to find some acceptable performance.

Initial perception and control tasks related to the human-robot interaction were evaluated with this simulation scenario. Although forces and torques applied on the robot can be modelled in this simulation, it is very difficult to simulate the response of the actual UR5e cobot, since it is unknown how the safety functions are operating in detail. Furthermore, the inertia parameters of the robot remain hidden by the robot manufacturer and the difficult process of parameter identification is required to calculate them. Therefore, this simulation should not be considered precise when it comes to human-robot interaction, and caution should be applied.

Modelling human actions is a challenge, especially for complex and versatile tasks as the ones studied in this application. In this simulation scenario, the human worker has been considered static, while it is perceived by the simulated 3D sensor. This results in predictable, but simplistic, behaviours on behalf of the cobot. In the later stages of the simulation process, task allocation will be considered and more accurate human behaviour modelling will be required.

4.1.4. End-effector design

The available commercial finger grippers are usually made of heavy-duty metallic materials, and their design includes several sharp edges and pitch points. For this collaborative process, a safer gripping solution was required, tailored to the needs of the problem. Thus, a new two-finger gripper, illustrated in Figure 4, was designed.

The finger gripper is actuated with electrical servo motors that provide feedback on both position and current. Especially the latter can be useful to detect excessive forces through its indirect real-time measurement. Patches from flexible materials are mounted on the gripper's fingers to minimize impact while grasping.

The gripper is made with additive manufacturing processes within ICCS premises. This way it is possible to create complex geometries that do not include sharp or shear edges, enhancing the safety of the application. Materials used in these processes are lighter and softer than common metals like aluminum, making a collision less severe. More precisely, the chosen material is ABS (Acrylonitrile butadiene styrene), since it has some of the lower densities of 3D printed materials, while having sufficient strength. The total mass of the gripper chassis and motors carried by the robot has been measured to approximately 0.7 kilograms.

Using additive manufacturing multiple designs with minor adjustments of their geometry can be tested and evaluated for the pick-and-place operations, while still in prototyping phase. Finally, in case of a severe gripper collision, "printing" a new component of the gripper that failed is cheaper and a matter of hours instead of ordering one of its components or a new commercial gripper to replace it.

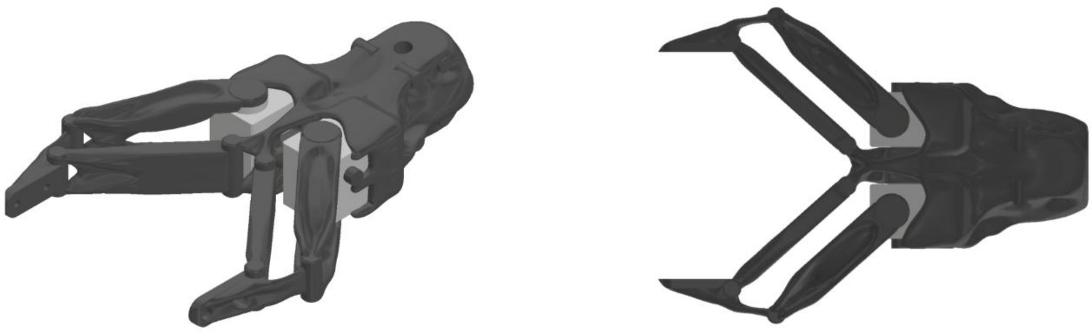

Figure 4: Two finger gripper designed for this collaborative application

In later stages, based on the needs of application several additional integrations on the existing gripper design will be considered to enhance safety and usability. Example integrations are buttons on the gripper to control its operation or trigger an emergency stop, lighting to denote current operation e.g. currently actuated, and capacitive or similar sensors to detect collisions with the environment and human workers. Finally, more flexible materials like TPU (Thermoplastic Polyurethane) and TPE (Thermoplastic Elastomer) will be tested in later stages.

4.2. Extended Reality Interfaces

For all the XR modalities (HMD, video wall, backlit conveyor), the task assignment from the perception module via the task planning module is communicated on an MQTT topic that includes the location of an object on the conveyor at a specific point in time, with the corresponding timestamp, and its destination according to its classification type.

4.2.5. Head-Mounted Display

The MR application for HMDs was developed in the Unity platform. A virtual scene was created comprising a conveyor belt moving a stream of virtual objects, a cobot next to a workbench and several bins (Figure 6). In this mixed-reality scene, various conveyor speeds and visual messages to indicate to the user their assigned tasks were tested to gain a better understanding of what the actual process in a real setting would entail. This work was presented in the application track segment of the EuroXR 2024 Conference (Bolierakis et al., 2024).

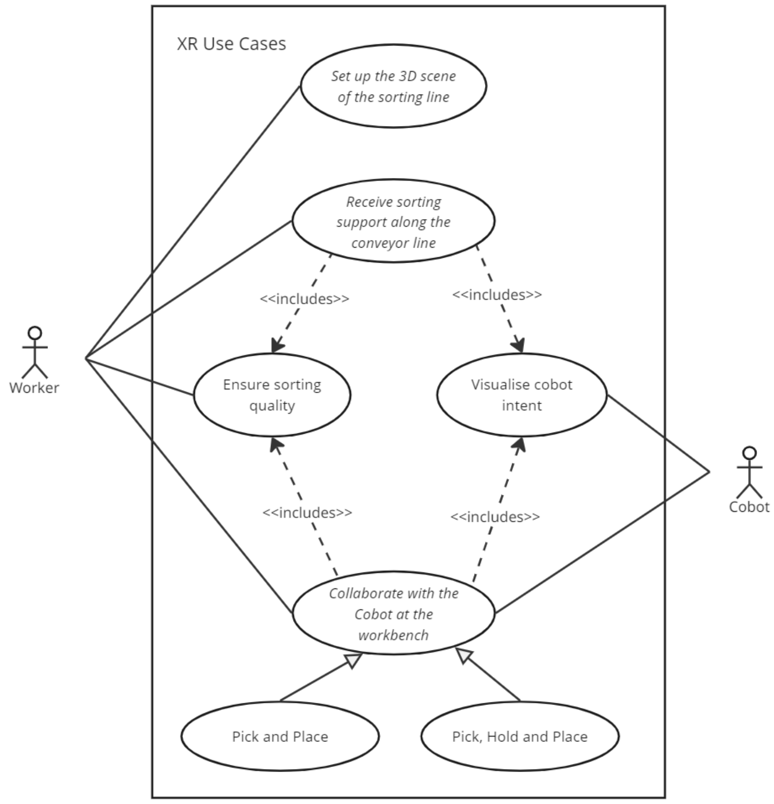

Figure 5. Use case diagram for the MR HMD application.

An overview of the functional requirements that will guide the completion of the final version of the MR HMD application is illustrated in the use case diagram shown in Figure 5, with the two main actors being the worker and the cobot. *Setting up the 3D scene of the conveyor line* entails the spatial alignment of the virtual scene with the real scene, which is commonly achieved via the detection through the HMD of markers with known positions in the virtual scene. *Receiving sorting support along the conveyor line* entails the visualisation of instructions which convey the task allocation in a user-friendly way. *Collaborating with the cobot at the workbench* also provides instructions on the collaborative task. Both the last two use cases include two important steps: i) visualisation on the HMD of the next intended movement of the cobot so that the worker is aware of its next move (*Visualise cobot intent*) and ii) user interface controls for the worker to be able to communicate to the system about inaccuracies that they have visually identified in case they do not agree with the received instruction (*Ensure sorting quality*).

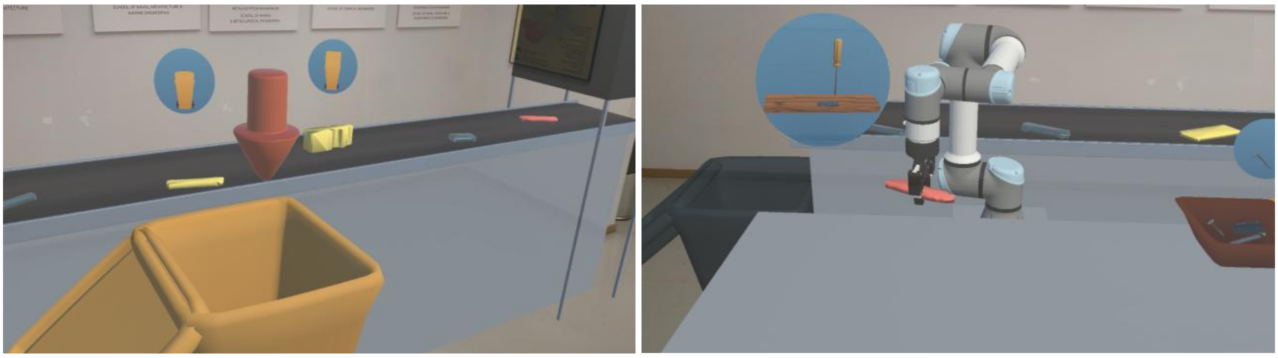

Figure 6. Views of the XR HMD user interface from the developed prototype. (Left) Along the conveyor, the worker is shown instructions, overlayed to wood pieces, which convey each object's destination bin. (Right) At the workbench, the worker receives an indication of the task that has been identified for the object picked by the cobot.

4.2.6. Video Wall

The most straightforward way to visualise instructions for a worker to follow is on a monitor. To this end, an 1x8 monitor video wall was put together and placed along a conveyor (Figure 7). The physical dimensions of the video are 0.41x5.68 m and the total resolution is 1080x15360 pixels. The video wall is showing the full width of the conveyor belt and everything on it for the length of the belt in front of the video wall. The image is in practice a mosaic that is created from the frames extracted from the video stream of an RGB camera in the perception unit. Each frame is corrected for lens distortion and perspective distortion and orthorectified with the assumption of relatively planar objects at the level of the conveyor belt; an assumption that holds well for small wood chips. The instructions to the user and the object they correspond to are added as annotations and highlights on the mosaic itself. The main disadvantage of this approach is that the information about an object is not overlayed on the object directly but on an image of the object that moves with the object. In the final version of the video wall interface, the 3D shapes of the objects will be taken into account in order to more accurately orthorectify the raw image frames and generate a true orthomosaic.

Figure 7. A section of the video wall that will be used in the XR-based collaborative sorting trials in W2W.

4.2.7. Projection-Based Augmented Reality

The premise of the projection-based AR configuration for the collaborative sorting line is similar to but more straightforward than that of the video wall as the projectors are in practice monitors. The required spatial calibration was performed with the projector-camera calibration toolbox by Moreno and Taubin (2012). The projected images comprise instructions and highlights of the related objects. At this point, highlights are projected on the objects on the conveyor belt. In the next iteration, textual information will also be projected on a custom made projection screen along the conveyor belt.

4.2.8. Backlit Conveyor

For the LED-based XR modality, a conveyor was tailor-made to include a translucent bed (the top horizontal part of the conveyor frame) and translucent belt so that LED strips, which are fixed to a surface underneath, highlight objects of interest. Sixteen 5-meters long strips, comprising 150 individually addressable LED each, were used to create this low resolution screen. The spatial separation between LED is 3.3 cm with an total effective width of 40 cm. Each item moving on the conveyor, on which an predefined action needs to be performed by a worker, is highlighted based on an intuitive colour-coded schema, e.g. items that need to be removed from the stream altogether highlighted in red.

5. TECHNICAL SPECIFICATIONS

Table 1 lists the technical characteristics of the main components used in the prototyping phase.

Table 1. Technical Specifications

Component	Characteristic
Conveyor	optimal belt speed for collaborative scenarios: 0.5 m/s belt width 0.5-0.7m top of belt height from the floor: 1.1 ±0.1 m
Perception Module	RGB-D camera (indicative model: Intel Realsense D435i)
Cobot	Universal Robot UR5e
End-effector	Custom-made finger gripper, actuated with servo motors, made with additive-manufacturing processes
HMD	Microsoft Hololens 2
Video Wall	eight 32” FHD monitors attached to floor stands two 4-channel FHD video wall controllers
Projection-based AR	two short-throw projectors with 0.75:1 throw ratio 8000 lumens
Backlit Conveyor	sixteen individually addressable LED strips, 5 m long 30 LED per meter two 8-channel ESP32-based LED controllers
Operating system	Ubuntu 22.04 LTS (without a real-time kernel)
Robot framework	ROS2 Humble
Robot planning & control framework	MoveIt2 (https://moveit.ai/)

6. CONCLUSION

The most challenging aspect of designing and implementing a human-robot collaborative scenario is identifying a use case for which the collaboration is beneficial to the worker in terms of safety, wellbeing and productivity. The first phase of the implementation and prototyping of the wood-sorting collaborative process was dedicated to defining a use case that can add value to the W2W sorting component, designing it in a way that will lead to impactful results during is completion at the end of the project. Several XR modalities have been prototyped so that in the demo we are able to assess the practical use of a HMD during sorting activities against more conventional set ups. The next phase of the project will start with planning the trial and demonstration activities that need to be supported for quality wood sorting and finalise the development of all the collaborative features and quality checking features.

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